DECREMENTS IN HUMAN PERFORMANCE DURING 72-84 HOURS OF SUSTAINED OPERATIONS

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ABSTRACT

Purpose: This study examined the effects of 3.5 days of sustained military operations (SUSOPS) on physical and cognitive performance and thermoregulatory responses to cold stress. **Methods**: Thirteen male soldiers participated in this study. The experiment consisted of 84-h (from 0600-h on Day 1 to 1800-h, Day 4) of physical activity with limited time allotted for sleep. Sleep was restricted by scheduling only limited blocks (1-h for each sleep period - total of 6-h). On the previous week, subjects were not sleep deprived or in a negative energy balance (CONTROL week). Subjects completed a battery of physical and cognitive performance tests and a cold-air test on each week at various time points. **Results**: The SUSOPS scenario was physically and mentally challenging as evidenced by the estimated caloric deficit (~3,000 kcal·day^{-1}), the loss in body mass (~3.1%), the limited amount of sleep achieved (total of 6.2 h), and the continuous scheduling of physical activity (~22 h/day). Fat-free mass (-2.3%) and fat mass (-7.3%) declined in the Soldiers during SUSOPS. Squat jump mean power (-9%) and total work (-15%) declined during SUSOPS. Bench press power output, grenade throw, and marksmanship for pop-up targets were not affected. Obstacle course and box lift performances were lower after 48-h but showed some recovery at 72-h. Wall building was ~25% lower during SUSOPS. Decrements in visual vigilance, choice reaction time, and matching-to-sample were observed. All mood states assessed by the POMS (tension, depression, confusion, vigor, fatigue and anger) deteriorated. During the cold air trial, rectal temperature decreased to a greater extent after SUSOPS (0.52 ± 0.09°C) vs. Control (0.45 ± 0.12°C) with the threshold for shivering lower following SUSOPS (34.8 ± 0.2°C) vs. Control (35.8 ± 0.2°C). **Conclusion**: This study demonstrated that while decrements in a Soldier's physical performance can be expected during short term operational stress, these decrements are primarily restricted to tasks that recruit muscle groups that are over-utilized without given adequate recovery or during tasks that require high levels of persistence. The decrements in cognitive performance are similar to those observed in highly stressful field studies. These results also indicate that 84-h of SUSOPS leads to greater declines in core temperature, increasing susceptibility to hypothermia.

1. INTRODUCTION

Military sustained operations (SUSOPS) expose soldiers to extended periods (many days) of multiple stressors. These stressors include exertional fatigue, sleep deprivation, and energy deficits. These stressors can, individually, impair physical and cognitive performance (Friedl et al., 1994; Friedl, 1995; Lieberman, 2005; Nindl et al., 1997) and degrade thermoregulation (Castellani et al., 2001; Kolka et al., 1984). The combined effect of these stressors on soldier performance has not been examined.

The purpose of this study was to develop a laboratory-based model of SUSOPS and determine the impact of the multi-stressor environment on physical and cognitive performance and thermoregulation in the cold. It was hypothesized that several days of prolonged work, sleep deprivation, and limited food intake would reduce mean power during repetitive ballistic performance, lower maximal work productivity during physically exhausting work, compromise military skill tasks and performance during self-paced work, reduce cognitive performance, and blunt both shivering and vasoconstriction. This paper summarizes the results of three experiments from this study recently published in the open literature (Nindl et al., 2002; Castellani et al., 2003; Lieberman et al., 2006)

2. METHODS

2.1 Experimental Design

This study utilized a within-subjects repeated measures design consisting of two 84-h testing blocks. Cognitive and physical performance tests were completed on the morning of Day 1 (D1), D3, and D4 of each test week. The initial block (Control Week) included the experimental tests but no other scheduled exercise. Sleep and food intake were *ad libitum*. The following week (SUSOPS), the second 84-h test block was performed. Cognitive and physical performance tests were again completed on the morning of D1, D3, and D4. The experimental SUSOPS week consisted of 84-h (from 0600-h on Day 1 to 1800-h, Day 4) of physical activity with limited time allotted for sleep and energy intake was less than energy expenditure. Forty-nine hours of this time period were spent doing military-relevant field exercises. Sleep was restricted by scheduling only limited blocks (1-h for each sleep

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period) and keeping soldiers busy performing mental and physical tasks for the majority of each 24-h day. Sleep patterns were monitored via actigraph activity monitors (Mini Mitter Co., Inc., Bend, OR and Precision Control Design, Inc, Fort Walton Beach, FL). Sleep time was calculated by adding the time periods where no movement was detected. Actigraphy indicated that subjects slept for a total of 6.2 ± 0.4 h during the 84-h SUSOPS period.

Subjects consumed one US Army MRE (range 1,100-1,352 kcal) per day during the SUSOPS week, supplemented with one bagel, juice, and a piece of fruit on the morning of Days 1, 3, and 4 and a candy bar on Day 2. Thus, the subjects consumed an average of 1,653 ± 25 $kcal \cdot d^{-1}$ (225±6 g carbohydrate, 54±2 g fat, 69±3 g protein). Subjects had free access to water throughout each week. The estimated mean total daily energy expenditure was ~4500 $kcal \cdot d^{-1}$ which was based on body mass and the estimated energy cost of the activities performed.

2.2 Physical Performance Tests

Subjects completed the following battery of physical performance tests each week on the morning of Days 1, 3, and 4:

Maximal Strength - Maximal lifts in the squat and bench press exercises were determined during preliminary testing. With the barbell placed on the shoulders, a successful parallel squat required descending by flexing the knees and hips until the proximal head of the femur reached the same horizontal plane as the superior border of the patella. The subject then returned to a standing position. For the 1-repetition maximum bench press, the subject gripped the barbell slightly wider than shoulder width and lowered the barbell under control until it lightly touched (i.e., without bouncing) the chest. The subject then lifted the barbell back to a straight-arm position while keeping the feet and hips in contact with the floor and bench. All strength testing was conducted on a MaxRack (Max Rack, Inc., Columbus, OH). Warm-up consisted of performing 5-10 repetitions at 40%-60% of perceived maximum, a 3-5 min rest and stretching period, and the completion of 3-5 repetitions at 60%-80% of maximum. Three to five subsequent lifts were then made to determine the 1-RM with 5 min of rest between lifts. An attempt was considered successful when completed through a full range of motion without deviating from proper technique and form.

Ballistic Power Tests - A repetitive bench press throw and squat jump test were used to elucidate the impact of SUSOPS on upper body and lower body ballistic power. Subjects were required to perform 30 consecutive repetitions at a load of 30% of their 1-RM. This load was chosen as muscle efficiency is near maximal at 30% of maximal voluntary contraction (20,33). All testing was performed in a ballistic, explosive manner on a MaxRack (Max Rack, Inc. Columbus, OH) interfaced with a ballistic measurement system (Optimal Kinetics, Muncie, IN). For the bench press throw, subjects started with the arms extended straight over the shoulders and were instructed to throw the bar as high as possible at the end of the concentric movement to produce the maximum power output. The subject caught the bar on its descent and immediately, without pause, initiated another maximal bench press throw and continued until 30 repetitions were completed. For the squat jump, subjects squatted to a self-selected depth necessary for optimal vertical jump height then explosively jumped with the load as high as possible. After descent, the subjects, without pause, initiated another jumping movement and continued until 30 repetitions were completed. Mean power (W), peak power (W), mean velocity ($m \cdot s^{-1}$), peak velocity ($m \cdot s^{-1}$), maximum displacement (m), minimum displacement (m), and work (J) were calculated.

Repetitive Box Lift (RBL) - To assess manual material-handling capability, the subjects lifted as many 20.5 kg metal boxes (0.47 m x 0.23 m x 0.31 m; with side handles) onto a 1.3 m high platform as possible in 10 minutes. This test simulates loading a truck as fast as possible and requires muscular strength and endurance. Encouragement was provided throughout the test to motivate the subjects to perform maximally. During the test the subject was positioned in between two platforms spaced 2.4 m apart. After the subject lifted a box onto the platform in front of him, he turned 180°, stepped up to the other box, and lifted again. Technicians lowered the box to the ground after each lift, so that the volunteer lifted but never lowered the boxes. Total work (J) performed during the test was calculated and used for statistical analysis.

Obstacle Course (OC) - Soldier mobility was assessed via a six station indoor obstacle course that simulated impediments to movement that a soldier might encounter during a conflict. Rapid navigation of the course required high levels of speed, strength, coordination, agility, and anaerobic endurance of both the lower and upper body. The first course obstacle was a set of five 46-cm-high plastic hurdles, spaced over 16.8 m. The subjects then ran a zigzag pattern around 9 staggered plastic cones covering a distance of 26.8 m. They then rounded a corner and low-crawled through a 3.7-m-long wood frame tunnel (61 cm high and 91 cm wide). Upon exiting the low-crawl, the volunteers shimmied along a 3.7-m-long pipe suspended 2 m above the ground, a movement requiring them to hang from the pipe upside-down, with the legs crossed around the pipe, and advance by pulling with their hands. The next obstacle was a 137-cm-high wooden wall, over which the subjects climbed or bounded. Subjects finished the OC by running around a 180º corner and sprinting 28.7 m. The subjects performed two trials on each test day.

Times were obtained for each course segment using a light-beam system with telemetry (Brower Timing Systems, Salt Lake City, UT). The best time for each day was used for statistical analysis.

Grenade throw - In order to directly assess a combat-related military skill, grenade throwing accuracy was measured. In a standing position, subjects threw a dummy grenade at a target 35 m away. Five separate throws were attempted at a circular target. A throw was considered a "hit" if it was thrown within 5 m of the target. The grenades were the same shape (spherical) and mass (0.5 kg) as live grenades. For scoring, the number of hits and the distance from the center of the target were recorded.

Marksmanship - Evaluation of M16 rifle marksmanship was conducted using the Model 70 Weaponeer Rifle Marksmanship Simulator (Spartanics, Rolling Meadows, IL) that employs a demilitarized M16A2 rifle and incorporates a realistic simulation of recoil. The subject was required to assume a standing foxhole position and first fire nine shots at a scaled 25-meter zeroing target, then fire at a mix of 50 stationary and moving targets (inter-target interval ≤ 1 s) presented singly and in pairs. Dependent measures assessed were number of targets hit out of 50 (SCORE) and number of shots that fit inside a 4 cm circle of the 25-meter zeroing target (SHOT). The last parameter is a measure of shot tightness.

Wall-building - Physical persistence, defined as the ability to maintain a prolonged repetitive physical task, was assessed by means of a wall-building task. This test was selected because it is a monotonous, repetitive task, much like assembly line work and performance is limited by factors (e.g., drive to perform) other than muscle strength and endurance (23). Subjects were instructed to build as many 10 x 10 block walls in 25 min using 100 wooden blocks (2 x 4 x 8 inches). Each block weighed less than 0.2 kg. Subjects were required to move the blocks a total of 5 m from a starting supply pile to assemble a wall. After a wall was built, the blocks were rapidly dispersed into a pile by a technician for the volunteer to move back to the initial location 5 m away to build a second wall. This process was continued for the 25 min. The task was self-paced with no verbal encouragement given. A "one-minute-to-go" warning signal was given 24 min into the test.

2.3 Cognitive Performance Tests

Subjects completed the following battery of cognitive performance tests each week on the morning of Day 1, 3, and 4:

Visual Vigilance - This test assesses vigilance, which is the ability to sustain attention during long, boring, continuous tasks that generate minimal cognitive load. The volunteer continuously scans the computer screen to detect the occurrence of an infrequent, difficult-to-detect stimulus that appears at random intervals and locations on the screen for 2 sec. On average, a stimulus was presented once per min. Upon detection of the stimulus, the volunteer pressed the keyboard space bar as rapidly as possible. The computer recorded whether a stimulus was detected and time required for detection. Responses made before or after stimulus occurrence were false alarms. Each test session lasted 20 minutes.

Four-Choice Reaction Time (RT) - This test assesses ability to respond rapidly and accurately to simple visual stimuli. Volunteers were presented with a series of visual stimuli at one of four different spatial locations on the computer screen. They indicate the correct spatial location of each stimulus by pressing one of four adjacent keys on the keyboard. Parameters recorded included correct and incorrect responses, RT, premature errors (responding before presentation of the stimulus), and time out errors (response latency greater than 1 sec). The test took approximately 5 minutes to complete.

Matching-to-Sample - This test assessed short-term spatial memory (working memory) and pattern recognition. The volunteer initiated a stimulus presentation by pressing the arrow key when "READY" appeared on the computer, after which a 7 x 7 matrix of a red and green checkerboard pattern was presented. The matrix appeared for 4 sec, was removed, and followed by a variable delay interval of either 1 or 15 seconds. Then two matrices were presented: the original matrix and a matrix with the color of two squares reversed. The volunteer attempted to select the matrix that matched the original sample. The task consisted of 30 trials, 15 for each delay presented in random order A response (left or right arrow key) was required within 15 sec, or a time out error was recorded. Correct responses were recorded, as was RT.

Repeated Acquisition - This test assessed motor learning, attention, and short-term memory. Volunteers learned a sequence of 12 keystrokes, using the four arrow keys of the computers. The outline of a rectangle was presented on the screen at the beginning of a trial. Each incorrect response blanked the screen for 0.05 sec. When the screen reappeared, the volunteer was at the same place in the rectangle as before. Volunteers learned the correct sequence by trial and error. When a sequence was correctly completed, the rectangle was filled, the screen blanked, and another empty rectangle reappeared for the next trial. A session ended when the volunteer completed 15 correct sequences. Incorrect responses and time to complete each trial were recorded. Time to finish this task was 10 minutes.

2.4 Cold Air Test

Subjects completed two cold air tests (CAT), one at the end of a control week of tests and another at the end of an 84-h SUSOPS. Cold air tests were conducted between 1300-1630 hours and Control and SUSOPS cold

air tests were spaced by one week. During the Control week, subjects were not sleep deprived or in a negative energy balance. However, they did perform a variety of physical and cognitive tests before undergoing the CAT (Figure 1). During the SUSOPS week, subjects performed the same physical and cognitive tests before the CAT, but overlaid on them was a limited amount of sleep and food (see below). The subjects were sitting in nylon-webbed chairs and dressed in only shorts, socks and woolen glove liners for the CAT. Baseline values for temperature, metabolic heat production, plasma norepinephrine, and thermal sensation were collected during a 20-minute period with conditions maintained at an air temperature of 25°C and 50% relative humidity (RH) with a minimal air velocity. Following this, ambient temperature (T_{amb}) was reduced by 0.5°C·min^{-1} over a thirty-minute period, after which T_{amb} was maintained constant at 10°C and 50% RH for an additional 150 minutes. Oxygen uptake, carbon dioxide output, and minute ventilation were measured by open-circuit spirometry at min 30, 60, 90, 120 and 150. Rectal temperature (T_{re}) and mean skin temperature were obtained every minute. While exposed to the cold, the subjects were not allowed to employ behavioral thermoregulation (no unnecessary physical activity or "huddling"). All subjects consumed the cracker and spread (380 kcal) from an Army Meal-Ready-to-Eat (MRE) ~105-min prior to each CAT to ensure that plasma glucose concentrations remained at normal levels throughout CAT.

2.5 Statistical Analysis

Data were analyzed using a two-factor (experimental trial X time) repeated-measures ANOVA. When significant F ratios were calculated, paired comparisons were made post-hoc using either a Tukey or Newman-Keuls test. The level of significance for differences reported is $P < 0.05$. Values are mean ± standard error (SE).

3. RESULTS

3.1 Physical Performance

Bench press throw performance was not affected by SUSOPS, with mean power averaging 351.6±22.7 W. In contrast, squat jump mean power (-8%) and total work (-14%) declined ($P \leq 0.05$) during SUSOPS. The performance decrement was associated with a shallower descent ($P \leq 0.05$) before initiating the jump.

Figures 1 and 2 show the changes in the OC and RBL performance. Both of these tests exhibited similar response patterns during the study, in that performance was decreased ($P \leq 0.05$) on SUSOPS D3, but demonstrated some recovery by D4 and performance scores were no longer statistically different from SUSOPS Day 1. The number of boxes lifted decreased with 8.5% less work completed on SUSOPS day 3 (D1: 5289.3±332 J vs. D3: 4848±325 J).

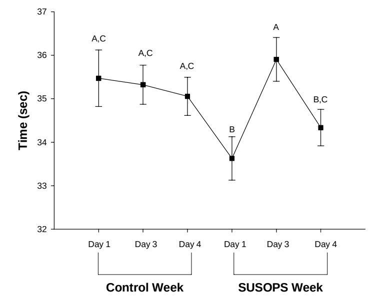

Figure 1. Changes in obstacle course time (sec) to completion during days 1, 3, and 4 of the control and SUSOPS week. Similar letters denote statistical similarity, while different letters denote statistical differences (P≤0.05).

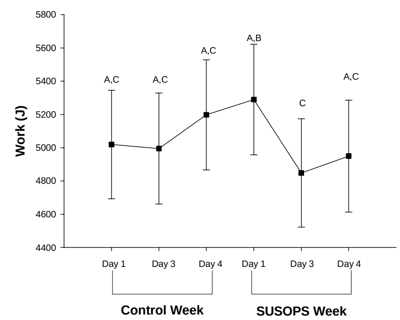

Figure 2. Changes in repetitive box lifting ability in work (J) done during days 1, 3, and 4 of the control and SUSOPS week. Similar letters denote statistical similarity, while different letters denote statistical differences (P≤0.05).

Wall building performance stabilized between D4 of the control week and D1 of SUSOPS week (figure 3). SUSOPS D3 (6.0±0.4 walls) and D4 (6.2±0.4 walls) performances were ~25% lower ($P \leq 0.05$) than SUSOPS D1 (8.0±0.4 walls). Grenade throwing ability and rifle marksmanship were not significantly altered by SUSOPS.

3.2 Cognitive Performance

Figure 3 presents the cognitive performance scores. For Visual Vigilance, the number of correct detections decreased over the duration of the study ($P<0.001$). For Four-Choice Reaction Time (RT), the number of correct responses decreased over the length of the study ($P=0.001$) while the total number of errors committed (premature and time-out) increased over the duration of the study ($P=0.009$). Total errors increased during the D4 test session of SUSOPS week compared to D1 and D3 of the baseline week and D1 of SUSOPS week ($P<0.03$). For Matching-to-Sample, the number of time-out errors increased over the duration of the study ($P=0.001$). On post-hoc testing, D3 and D4 were different from all other test sessions ($P<0.05$). No other parameters assessed by this task were affected by the experimental conditions.

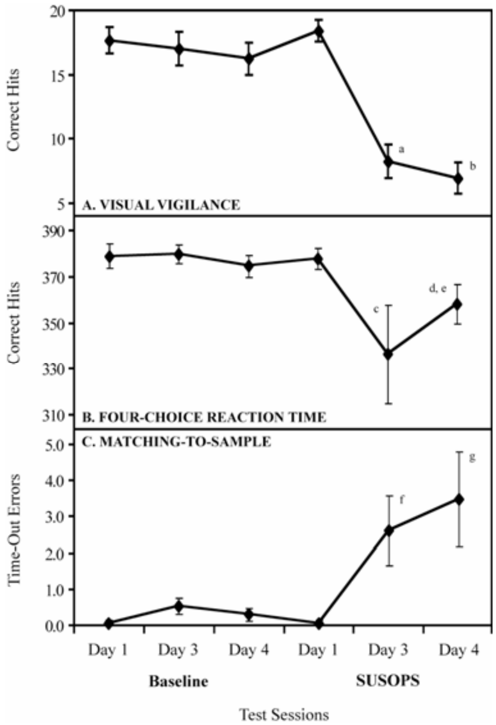

Figure 3. Mean (± SEM) cognitive performance across all testing sessions of baseline and SUSOPS testing blocks. Statistical significance is indicated by the following symbols: a) P<0.001 vs. all baseline days and SUSOPS day 1; b) P<0.001 vs. all baseline days and SUSOPS day 1; c) P≤0.05 vs. baseline day 1, 3 and SUSOPS day 1; d) P≤0.05 vs. baseline day 1 and SUSOPS day 1 ;e) P≤0.01 vs. baseline days 3 and 4; f) P≤0.05 vs. all baseline days and SUSOPS day 1; g) P≤0.05 vs. all baseline days and SUSOPS day 1.

3.3 Thermoregulation in the Cold

Metabolic heat production, an index of shivering thermogenesis, was significantly lower (P<0.05) at min 30 during the SUSOPS trial compared to the Control trial (Figure 4A). Metabolic heat production had a tendency to remain lower, although not statistically, through to min 90 in SUSOPS. Interestingly, metabolic heat production was significantly higher (P<0.05) in SUSOPS at min 150, compared to the Control trial. Oxygen consumption had the same pattern of response as metabolic heat production. RER was lower in SUSOPS (0.76 ± 0.04) vs. Control (0.87 ± 0.06) before the CAT and was generally 0.04-0.08 lower throughout the CAT in SUSOPS vs. Control. The relationship of the mean body temperature to the change in metabolic heat production is shown graphically in Figure 4B. The onset of shivering occurred at a lower mean body temperature (P < 0.05) in the SUSOPS (34.8 ± 0.2°C) trial compared to the Control (35.8 ± 0.2°C) trial. The slope of the $\overline{T}_b$ - ΔM relationship was greater (P<0.05) in the SUSOPS (-39.7 ± 8.1 $W \cdot m^{-2} \cdot °C^{-1}$) trial compared to the Control (-17.7 ± 2.4 $W \cdot m^{-2} \cdot °C^{-1}$) trial. These data indicate that shivering started later in SUSOPS, but once initiated, shivering increased to a greater extent per °C fall in mean body temperature in the SUSOPS trial.

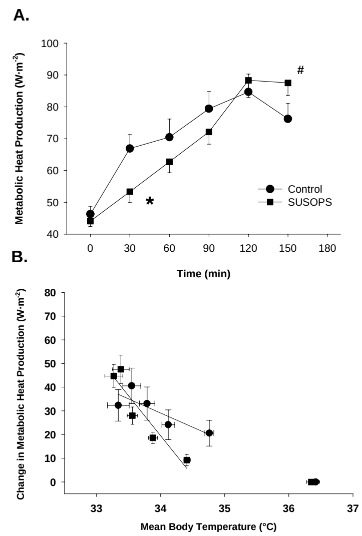

*Figure 4. **A**. Metabolic heat production ($W \cdot m^{-2}$) vs. time during 180-min cold air exposure (10°C) following Control and SUSOPS periods. * denotes SUSOPS is significantly lower than Control at min 30. # denotes SUSOPS is significantly higher than Control at min 150. **B**. Mean body temperature (°C) vs. change in metabolic heat production ($W \cdot m^{-2}$) during 180-min cold air exposure (10°C) following Control and SUSOPS periods. R values for Control and SUSOPS were 0.72 ± 0.04 and 0.80 ± 0.05, respectively.*

Rectal temperatures were similar between SUSOPS (37.25 ± 0.08°C) and Control (37.27 ± 0.09°C) trials at min 0 of the CAT. During the cold air test, core temperature was significantly lower (P<0.05) during the last two hours of cold exposure in SUSOPS compared to the Control trial (Figure 5A). Heat debt, calculated using thermometric methods, was significantly greater in the first 90 minutes of exposure in SUSOPS (Figure 5B). However, partitional calorimetry analysis indicated that heat debt was not significantly different (P>0.05) between SUSOPS and Control trials following 150-min of cold exposure. Mean skin temperature responses, an index of vasoconstriction although not as precise as measuring blood flow, were significantly (P<0.05) lower in the SUSOPS, vs. Control trial, at minutes 30, 60, and 90, with no differences at any other time period (Figure 6A). The T_{re}-$\overline{T}_{sk}$ gradient during the CAT is shown in Figure 6B. During the CAT after SUSOPS, the T_{re}-$\overline{T}_{sk}$ gradient was larger (P<0.05) than during the Control trial after 30, 60, and 90 minutes.

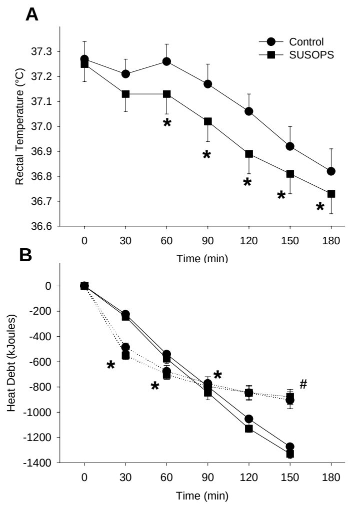

Figure 5. ***A***. *Rectal temperature (°C) vs. time during 180-min cold air exposure (10°C) following Control and SUSOPS periods.* ***B***. *Heat debt (kJoules) vs. time calculated by partitional calorimetry (solid lines) and thermometry (dashed line). * denotes significant difference between Control and SUSOPS at specified times. # denotes SUSOPS is significantly less than Control at min 150.*

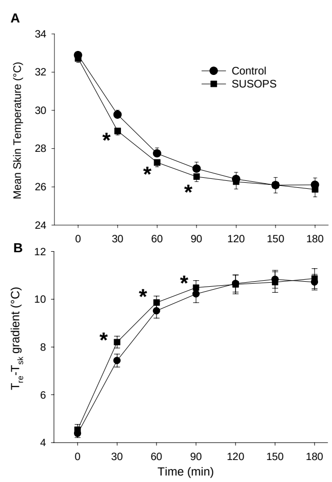

Figure 6. ***A***. *Mean skin temperature (°C) vs. time during 180-min cold air exposure (10°C) following Control and SUSOPS periods.* ***B***. *Thermal gradient (T_{re}-$\bar{T}_{sk}$) vs. time during 180-min cold air exposure (10°C) following Control and SUSOPS periods. * denotes significant difference between Control and SUSOPS at specified times.*

4. DISCUSSION

As performance is determined by both capability and motivation, physical performance tasks were specifically chosen to provide insight into both the physical and psychological effects of this stress and their impact on performance. Our findings demonstrate that short-term military operational stress adversely affect selected aspects of physical performance. An incremental and progressive decrement was observed for lower body ballistic anaerobic performance (D4 SUSOPS values were ~9% and ~15% lower than D1 SUSOPS values for mean power output and total work performed, respectively), while no changes were observed for upper body anaerobic performance or grenade throwing ability. Transient losses in performance were observed for OC and BL abilities, as these tests had declined at 48-h, but had statistically recovered by the end of SUSOPS. This study demonstrated that 3 out of the 4 physically demanding performance tests were negatively affected at some point during SUSOPS. However, it also underscores the resiliency of the body's physical performance capabilities during short-term operational stress, as only one power test (lower body ballistic anaerobic performance) was significantly compromised after 72-h of SUSOPS. It is perhaps a reassuring finding that well-learned soldier-related skills (grenade throw, marksmanship) are well maintained during short-term military operational stress.

In contrast to the modest changes in performance on tasks primarily limited by physical capability, there was a 25% reduction in wall building performance. The larger performance decrement with the wall build task is likely due to the persistence component of the task. The wall build task was a repetitive, monotonous task with no extrinsic verbal encouragement. The other physical tasks were of short duration and may have been influenced by high levels of extrinsic motivation (i.e., verbal encouragement). The wall build results suggest that prolonged and monotonous tasks will be compromised by prolonged work, sleep deprivation and underfeeding. A practical implication is that while this multi-stressor environment produces only modest decrements in physical capability, the reductions in persistence suggests extrinsic motivation in terms of verbal encouragement will be necessary to increase worker productivity.

Decrements in three of the four tests of cognitive function administered; Visual Vigilance, Four-Choice Reaction Time and Matching-to-Sample, were present by D3 of SUSOPS and were typically worse on D4; by contrast, performance was stable during the baseline week. Cognitive performance on D1 of SUSOPS was similar to performance during the baseline week since none of the SUSOPS stressors were present prior to the first test session of that week. On D3 and D4, 49-h and 73-h after the start of the SUSOPS week, simple tasks such as choice reaction time and vigilance were degraded by exposure to the SUSOPS scenario, as was a more complex task, Matching-to-Sample. The most complex task, Repeated Acquisition, a test of motor learning and memory, was not significantly affected.

These data suggest simple tests of cognitive performance are more sensitive to the effects of multistressor environments than complex tasks. This has been observed with regard to effects of some individual factors, such as sleep loss, caffeine or other nutritional interventions, on cognitive function (Amendola et al., 1998; Balkin et al., 2000; Lieberman, 2005). However, deficits in higher order cognitive functions are

sometimes observed in multistressor environments, as documented using the Repeated Acquisition test and other complex tests of information processing and logical reasoning, such as grammatical reasoning (Lieberman, 2005a). Differences in the severity of stressors present and number of volunteers tested in different studies probably contribute to these differences. Variability in performance of these complex tasks also contributes to their reduced sensitivity to both single treatment variables and multistressor environments (Lieberman et al., 2002; Lieberman et al., 2005).

The principal finding for thermoregulation in this study was the greater fall in core temperature during cold-air exposure following 84-h of SUSOPS, compared to the control trial, although the vasoconstrictor responses were not impaired, as hypothesized, following SUSOPS. Several factors might explain the lower core temperature after SUSOPS. One possibility is a blunted shivering response indicated by the delayed onset of shivering following SUSOPS, compared to rested conditions. Another possibility is that during cold-air exposure following SUSOPS, there was a redistribution of heat from the core to the periphery due to a higher thermal gradient, thereby causing a greater fall in core temperature.

Volunteers in this study slept for ~6 hours over 3.5 days and thus were sleep deprived. Recent data supports the idea that sleep deprivation, in combination with negative energy balance, impairs the shivering response. Young et al. (1997) found the shivering response was not initiated until a lower mean body temperature was achieved after enduring a multi-stressor training school before beginning their initial experimental cold exposure. However, it is difficult to attribute the changes in shivering thermogenesis solely to sleep deprivation in that study due to the multiple stressors present. Studies examining sleep deprivation, independently, have generally observed no effect on core temperature responses to cold exposure, but the methodologies and study protocols preclude definitive conclusions. Fiorica et al. (1968) observed no effect on shivering and vasoconstriction following 82-h of sleep deprivation. However subjects did not serve as their own controls and baseline core temperature in their control group progressively increased over 4 days, despite testing at the same time of day, which confounded data interpretation. Kolka et al. (1984) measured thermoregulatory responses during exercise in cold air (0°C) following 50-h of sleep deprivation and observed impairments in heat dissipation mechanisms during exercise that resulted in greater heat storage and elevated core temperatures. Thus, that study (Kolka et al., 1984) did not examine physiological adjustments (shivering, vasoconstriction) needed to prevent a fall in core temperature. Savourey and Bittel (1994) utilized a 27-h period of sleep deprivation, which was likely too short a time to cause a treatment effect on core temperature responses. Interestingly, in contrast to our finding of a delayed shivering response, Savourey and Bittel (1994) found that sleep deprivation increased the sensitivity of the shivering response, i.e., shivering began earlier. However, that study used a subjective measure of shivering to determine onset as opposed to an objective measure such as changes in metabolic heat production. Thus sleep deprivation effects on thermoregulatory responses to cold are unclear. Sleep deprivation may play a role by changing the set-point temperature at which physiological responses are regulated. Following both a multi-stressor scenario (Opstad and Bahr, 1991) and sleep deprivation alone (Kolka et al. 1984), core temperature was lowered ~0.5°C at rest before beginning exercise, but neither of these studies provides conclusive evidence of a reduced set-point.

Volunteers in this study had a 2800 kcal·day^{-1} caloric deficit. Previous studies suggest that underfeeding, despite normal glucose concentrations, impairs thermoregulatory responses to cold (Macdonald et al, 1984; Mansell et al., 1989; Young et al., 1998). In one study (Young et al., 1998), it is difficult to discern whether underfeeding was responsible for the blunted shivering response because there were large changes in body composition. In the other two studies (Macdonald et al, 1984; Mansell et al., 1989) subjects consumed no food for 2 days before testing and changes in the core temperature-metabolic rate relationship were measured after this 48-h fasting period. Unlike the changes seen in the present study (a decrease in the shivering onset, i.e., a temperature threshold change along with an increased gain), Macdonald et al. (1984) found a reduced gain (sensitivity) in the metabolic rate-core temperature relationship after 2 days of fasting in men. Similarly, a decline in the metabolic rate response to cold after fasting was observed in women following 48-h food deprivation (Mansell et al., 1989). The different shivering responses to the underfeeding stress between these studies and SUSOPS may be due to the type of underfeeding. In SUSOPS, subjects ate (including 2-h before exposure) but were underfed relative to their energy expenditure, whereas in the other two studies, subjects were sedentary and consumed no food at all. One possibility is that the diminished metabolic heat response is due to an elevated basal norepinephrine level that has been observed following either 48-h of fasting (Mansell et al., 1989) or a combination of sleep loss, underfeeding, and exertional fatigue (Young et al., 1998), which may lead to a down-regulation of beta-adrenergic receptors. However, our SUSOPS scenario did not increase resting plasma norepinephrine values.

5. CONCLUSIONS

Our laboratory-based SUSOPS model was effective in recreating actual sustained operations inducing performance and thermoregulatory decrements. This

SUSOPS model could be used to model appropriate work/rest ratios, determine optimal feeding schedules, identify ergogenic aids, improve physical training programs, identify appropriate manpower selection and allocation, and aid in planning for personnel replacement.

Approved for public release: distribution is unlimited. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

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